SkinPaper: Exploring Opportunities for Woven Paper as a Wearable Material for On-Skin Interactions

Jingwen Zhu
Hybrid Body Lab, Cornell University
Ithaca, USA
jz497@cornell.edu

Nadine El Nesr*
Hybrid Body Lab, Cornell University
Ithaca, USA
nme32@cornell.edu

Nola Rettenmaier *
Hybrid Body Lab, Cornell University
Ithaca, USA
ner45@cornell.edu

Hsin-Liu (Cindy) Kao
Hybrid Body Lab, Cornell University
Ithaca, USA
cindykao@cornell.edu

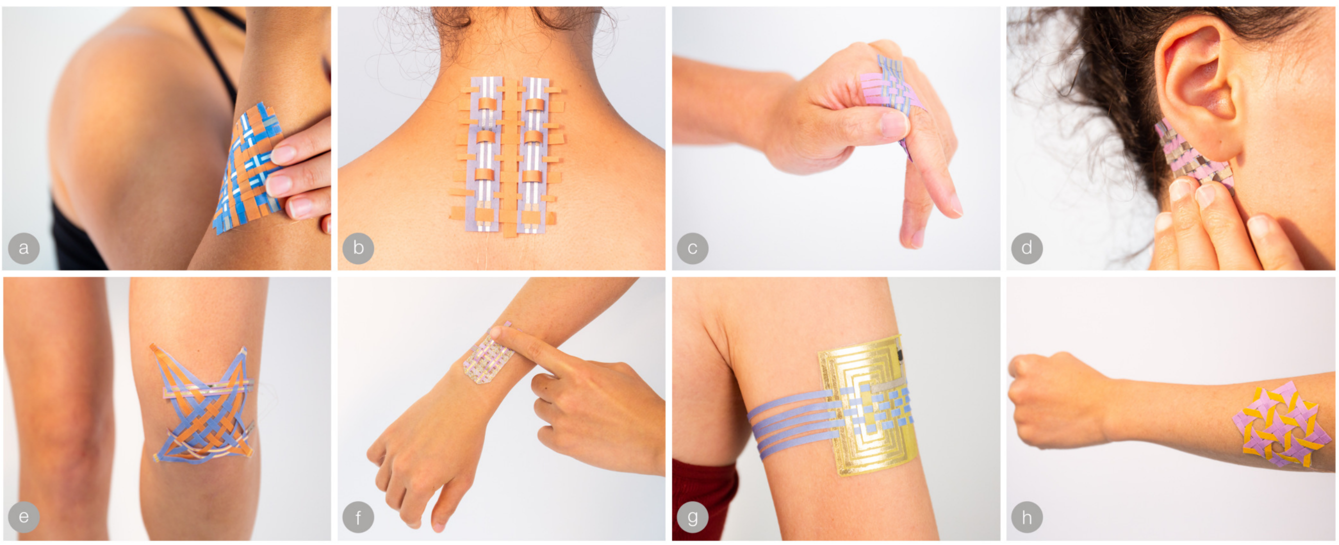

Figure 1: SkinPaper uses silicone-treated washi paper to weave lightweight and easy-to-fabricate on-skin interactions. Adopting a research-through-design approach, we contribute a design space with case studies that explore the variety of patterns, textures, and structures SkinPaper could afford: (a) A plain weave touch sensing matrix. (b) A protruded dome texture for LED diffusion. (c) A tubular finger touch sensing slider. (d) A behind-ear fuzzy weave touch input. (e) A 3D knee heating patch. (f) Collapsible textures as pressure input. (g) A twill weave NFC Tag with cut slits. (h) A double weave thermochromic patch.

ABSTRACT

Paper circuitry has been extensively explored by HCI researchers as a means of creating interactive objects. However, these approaches focus on creating desktop or handheld objects, and paper as a wearable material remains under-explored. We present SkinPaper, a fabrication approach using silicone-treated washi paper to weave lightweight and easy-to-fabricate on-skin interactions. We adopt techniques from paper weaving and basketry weaving practices to create paper-woven structures that can conform to the body. Our approach uses off-the-shelf materials to facilitate a highly customizable fabrication process. We showcase eight case studies to illustrate our approach's two to three-dimensional forms. To understand the expressiveness of the design space, we conducted a workshop study in which weavers created paper-woven on-skin interactions. We draw insights from the studies to understand the opportunities for paper-woven on-skin interactions.

*Both authors contributed equally to this research.

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CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**.

KEYWORDS

on-skin interfaces, wearable computing, paper circuitry

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1 INTRODUCTION

Paper is a ubiquitous material widely used in everyday life. The accessibility and familiarity of paper make it a material commonly used for beginner-friendly crafting and design. In recent HCI research, paper circuitry has been widely explored through crafting conductors onto paper substrates [22, 24, 25] and combining origami and kirigami to create various paper electronic components [5, 72]. However, these approaches focus primarily on using paper circuitry to create desktop or handheld objects, and paper as a wearable material remains under-explored.

Paper has functioned as a wearable material in certain historical contexts. For example, washi paper, composed primarily of mulberry bush fiber, has been woven into garments [32]. Compared to commonly used printer paper made from wood pulp, washi paper is more durable, fibrous, and less prone to tears and rips. Its textile-like properties allow it to be cut or shredded into long and slim strips, which, when woven orthogonally, can create malleable and wearable structures. Taking inspiration from paper woven garments and the extensiveness of paper affordances, we conduct a research through design (RtD) investigation [14, 73] on the possibilities and potential of woven paper as a wearable material. Through extensive design explorations, we synthesize a design space and present a series of case studies that offer novel insights into the interactive potential of the SkinPaper approach.

Among wearable objects, on-skin interfaces, which most often appear in the form of temporary tattoos or skin stickers, provide interactions situated directly on the skin surface [21, 30, 31, 66, 67]. On-skin interfaces are usually fabricated with unconventional materials such as PDMS (poly (dimethyl) siloxane), hydrogels, or tattoo decal paper in order to be low-profile and planar to adhere to the skin seamlessly. While HCI research has sought to develop more accessible fabrication methods to manipulate these materials for on-skin applications, they still often require specialized machinery, and the materials remain intrinsically higher in cost. Paper, however, possesses a familiarity globally that is unmatched by other materials. The manipulation of paper requires minimal and accessible hand tools but can achieve a wide range of colors, shapes, textures, and structures. Taken together, its low cost, ready availability, and expressiveness are in sync with our goal of expanding access for prototyping such emerging devices.

We present SkinPaper, a paper-woven fabrication technique using silicone-treated water-repellent washi paper to rapidly prototype on-skin interfaces (Figure 1). Washi paper's cross-cultural familiarity through time and its material and structural properties make it an attractive conduit for the goals of this research. As a readily available and accessible crafting material, the nature of crafting with paper can be less intimidating. It could open the field of on-skin interface fabrication to a broader audience, empowering more diverse populations to take part in co-defining this new technology. Furthermore, because washi paper is previously untreated (unlike standard printer paper), its cellulose fibers are easily accessible to chemical treatments, making it a good material choice for water-repellent and resilient on-skin wearables. In addition, the rich materiality of washi paper enhances the affordance of on-skin interfaces by expanding its physical properties and expressive dimensions. The paper-woven fabrication approach extends weaving techniques to create interfaces with unique textures and three-dimensional structures without requiring specialized tools or machinery. In this paper, our main contributions are:

(1) SkinPaper, a fabrication approach for creating structure- and texture-rich multi-dimensional paper-based on-skin interfaces.
(2) We identify washi paper as the key material that enables a skin-safe and user-friendly fabrication process for paper-based on-skin interfaces. The washi paper is treated with an off-the-shelf silicone-based spray for on-skin compatibility.
(3) The extended paper weaving-derived approach can support rich 2D patterns, 2.5D textures, and 3D structures under-explored by prior on-skin fabrication techniques.
(4) We conduct technical characterizations of these materials' hydrophobicity, bendability, and tensile strength, along with a wearability study to investigate wearability factors, including durability when worn directly on the skin.
(5) We develop eight case studies to demonstrate the techniques and various functionalities afforded by SkinPaper, along with a workshop study to understand the creative potential of this new on-skin crafting technique.

2 BACKGROUND

While HCI research has investigated the fabrication process of paper crafts [26, 28, 71] and the integration of paper electronics [5, 7, 22, 24, 25, 38, 43, 51–53, 64, 72], the potential of paper circuitry as a wearable interface has yet to be fully explored. However, paper has historically been regarded as a wearable material, and in many cases, the boundaries between paper and textiles are indistinct. One prominent example is woven washi paper in traditional Japanese culture [32, 36]. While paper instinctively may not seem suitable for on-body wear, it can be made resilient and durable through specific fabrication processes. This is realized through two important strategies, which we provide background on here and expand upon for our specific on-skin context:

Washi paper as a wearable material. Traditional Japanese *kōzo* Washi paper has a long history of usage as a textile weaving material for garments [32]. Unlike typical printer paper made from wood pulp, *kōzo* washi paper is made from mulberry bush. It is one of the strongest materials for paper making, with fiber strands about 10 mm long (compared with 1mm for wood-pulp printer paper) [33]. While washi paper can retain durability when wet [32] and is launderable as paper clothing, further improving hydrophobicity (otherwise known as water-repellence) is critical for on-skin wear. This would help counteract sweat secretion, render paper resilient to water exposure, and achieve comfort. Hence, it was necessary to identify a suitable approach for improving the hydrophobicity of washi paper. Coating paper with a layer of wax is a straightforward approach. However, it results in a significant increase in thickness.

Recent materials science research has investigated the use of organosilanes, such as trichlorododecylsilane, to treat paper to achieve omniphobicity without increasing the thickness of paper significantly[55, 56, 69]. This process has provided opportunities for the paper to be used as a substrate for epidermal electronics. However, this process involves heating the coated paper at a specific temperature on a heating plate, and organosilanes are hazardous to handle. This requires chemistry equipment such as professional chemistry hoods with proper ventilation and calls for professional handling of hazardous waste. This increases the barrier for designers and HCI researchers with limited chemical lab access to use the silanization method for designing paper-based on-skin interfaces. In SkinPaper, we identified a unique and accessible method of treating paper to be hydrophobic for on-skin applications: using off-the-shelf silicone-based sprays to treat paper to achieve water repellency. This process is non-hazardous and does not require a chemical hood, making it easier for individual designers to create their own water-repellent paper material for on-skin use.

Rapidly and easily achieving structural integrity through paper weaving. The affordances of paper can be rapidly altered through simple manipulations of cutting, shredding, or folding into strips and weaving them into new structures. Coincidentally, washi paper weaving traditionally applied in clothing production presents increased malleability and integrity compared to an unwoven sheet of washi paper due to its woven structure. These two examples demonstrate the diverse materiality achievable through paper weaving. We take advantage of the ability to finetune the behavior of paper material by deploying various woven structures conducive to a variety of interactions and body locations.

For an on-skin context, we adopt techniques from paper weaving [57] and basketry weaving [3, 34], which render not only wearable and comfortable 2-dimensional structures but also support 3-dimensional structures ideal for conforming to curved body locations. Unlike basketry weaving where pliable materials such as bamboo and willow require additional steps of soaking the material to render it bendable, paper strips share a similar pliable feature while being much easier to manipulate. For instance, paper weaving is a beginner-level paper handcraft that even very young children can master [1]. The paper weaving process using just paper and scissors makes it significantly easier than textile weaving which involves more steps and the use of a loom.

3 RELATED WORK

3.1 Paper Circuity

Various conductive material application techniques have been explored within the field of paper electronics, including printing [8, 24, 25, 42, 43, 47], paint and spray [9, 35, 70], and adhering [16, 49, 51, 58]. Combined with paper crafting techniques such as origami and kirigami, a wide range of applications have been demonstrated in previous work, including sensing [5, 35, 72], actuating [7, 43, 50] and communication [41]. These paper circuitry solutions support a rich design space for paper-based interfaces.

Besides investigating conductive materials and methods, further research explored assembling surface mount components onto paper conductive traces [2, 35]. This provides a solution for a fully integrated paper circuitry. Projects such as paper-woven circuits [22] explored weaving paper to create circuits, giving an exemplary approach of how woven structures could increase the possibilities of designing and fabricating complex circuits with paper.

SkinPaper combines common paper circuitry techniques, such as stencil-based conductor crafting with paper woven structures, to create paper-based on-skin interfaces with rich functional and aesthetic design opportunities.

3.2 Woven Interfaces in HCI

Weaving involves the intersection of two groups of materials, often at a right angle, to form a surface. The use of tools and materials characterizes different techniques such as textile weaving, basketry weaving, or paper weaving. Basketry weaving and paper weaving are often handmade, while textile weaving requires the use of an apparatus (often a loom) to tension the warp (the lengthwise threads) due to the flexibility of the threads. In the HCI community, textile weaving has been most widely investigated [10, 11, 17, 27, 45, 48, 60], with only few research investigations in basketry weaving [61] and paper weaving [22]. In these weaving examples, by combining conductive or resistive materials with weaving, HCI researchers have explored a wide range of functionalities, including sensing [17, 44, 45, 60] and actuating [12, 27].

In SkinPaper, we expand beyond a focus on traditional textile weaving to an extended and versatile weaving approach. SkinPaper explores integrating both textile weaving and basketry weaving techniques into paper weaving to create 3D structured and shaped on-skin interfaces. Compared to textile weaving, basketry weaving is compatible with pliable materials such as paper, with the capability of involving more than two groups of strip materials and forming three-dimensional structures. The potential for three-dimensional designs afforded by basketry weaving extends the possibilities of basic planar textile weaving and can be used to generate innovative and interactive on-body designs.

3.3 On-Skin Interface Fabrication Approaches

On-skin interfaces extend device-based interactions to users' body surfaces. Previous research has examined the various functionality of on-skin interfaces, including sensing input [21, 30, 39, 62, 66, 67], displaying output [18, 21, 65, 67], and providing haptic feedback [15, 68]. This wide range of functionalities has demonstrated the potential for broad usage of on-skin interfaces in everyday life.

Advanced material science research has explored various materials to create thin and flexible circuitry for on-skin interactions, including PDMS (poly (dimethyl) siloxane) [66], hydrogels [19], or tattoo decal paper [20, 21, 23, 23, 30, 39, 67]. HCI researchers have developed corresponding fabrication methods including laser patterning [39], vinyl cutting [21, 30], and casting [66]. The form factor of the material results in a planar and smooth surface that conforms to the skin and provides rich functionalities.

All the previous methods require advanced material tuning. Conversely, paper crafting techniques are less expensive and easier to manipulate. Through folding, scoring, and cutting, one can create paper crafts without any prior crafting skills. Paper crafts do not require specific machines; commonly accessible tools like paper cutters (for cutting) and tweezers (for detail handling) are sufficient to accomplish the versatile materiality of paper-woven interfaces.

SkinPaper utilizes paper crafting methods for on-skin interface fabrication, to create textured and structured on-skin interfaces with accessible tools and materials.

4 SKINPAPER DESIGN SPACE

Here, we identify opportunities for a paper-based material system to enable on-skin interactions. We adopted a research through design method [14, 73] to explore the emergent materiality of paper-woven on-skin interfaces. A twofold design space (Figure 2), consisting of (A) the Paper Primitives and (B) Woven Structuring Techniques, is synthesized through the research team's extensive design experiences over a nine-month period, in which we explored numerous weaving techniques, fabricated hundreds of sample swatches, and conducted a literature review of various forms of weaving (paper [32, 57], textile [4, 11], to basketry [3, 61]).

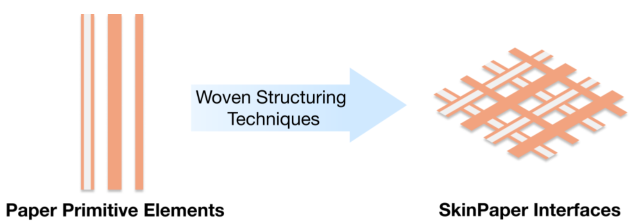

Figure 2: We defined a twofold design space consisting of (A) Paper Primitive Elements and (B) Woven Structuring Techniques to create SkinPaper Interfaces.

Design Considerations: Important design considerations for paper-based on-skin interfaces include:

- The materials and process for fabricating paper-based on-skin interfaces need to be user-friendly. The process should use off-the-shelf materials and accessible fabrication techniques.
- Wearability is critical. The interfaces must be skin-safe, durable, and sufficiently stretchable to be applied to body locations.
- The interface should be versatile structurally and texturally. It needs to employ paper's unique properties to create versatile tactile textures and three-dimensional structures that can conform to various body locations.

4.1 (A) Paper Primitive: Hydrophobic Washi Paper

4.1.1 (a) Paper Primitive Architecture. The primitive paper architecture for on-skin interfaces is a multi-layer structure shown in Figure 3(a). It consists of four layers: the base washi paper layer, the design layer, the hydrophobic layer, and the interaction layer.

Base Washi Paper Layer: We use traditional Japanese *washi* paper as the base material for realizing our paper-based on-skin interfaces. The superior toughness of the plant fibers paired with traditional hand-made procedures in the drying process allows the water to evaporate slowly, making it highly workable even when wet. The resulting product is comparatively more pliable, durable, and impermeable than other paper in the 60 to 90 μm thickness range, making it the appropriate material that meets our design considerations for fabricating on-skin interfaces.

Design Layer: To customize the base washi paper layer, one can either draw, stencil, or inkjet print visual design content. This design layer can be used for aesthetic purposes, such as printing colors and graphic patterns, as well as functional purposes, such as printing circuit layouts as guidance for crafting the interaction layer.

Hydrophobic Layer: We identified an accessible method leveraging non-hazardous off-the-shelf silicone-based spray to render the paper hydrophobic. This method has not only yielded hydrophobicity results comparable to a silanization procedure carried out in the fume hood using organosilane compounds but is also skin-safe and can be achieved even in a home lab setting.

Interaction Layer: The interaction layer enables the application or printing of conductive and interactive materials on the paper layer to create circuity. Based on different primitive element shape designs, the interaction layer can be applied in continuous traces, dash lines, or specific shapes and patterns.

4.1.2 (b) Weavable Paper Primitive Elements. To afford *weaving*, the hydrophobic paper needs to be pre-processed into weavable elements such as strips or have slits cut into the sheet itself for weaving in other elements (Figure 3(b)). Users can choose the size and shape of the paper primitives according to their skill level and desired fidelity of the prototype.

Straight-Strips: Straight stripes are a simple yet fundamental weavable element for paper-based interfaces. By tuning the width of the strips, the *materiality* of the resulting woven interface can vastly differ. For example, thin strips ($< 3mm$) interwoven create a malleable and cloth-like interface, while thicker strips ($> 6mm$) result in a more stiff, paper-like structure. Choosing suitable widths for specific body locations and applications is an important design decision. Meanwhile, thicker strips are beginner friendly and easier to weave quickly, while thinner strips would require more practice and time to create a refined woven structure.

Shaped-Strips: By customizing the outline of each strip, the interface can attain various shapes and properties. For instance, serpentine-shaped strips offer stretchability that linear strips lack. Tapered strips also provide structural integrity and surface area coverage that fits specific body locations.

Slits: Through cutting patterned slits, the paper primitive provides openings for weaving in other material elements. Slits can be open for creating 3D structures or closed for creating 2.5D textures.

4.2 (B) Woven Paper Structure Design Space

Paper weaving can incorporate techniques and structures used in basketry and textile weaving. This versatile compatibility allows us to create various 2D patterns using simple strip-shaped paper primitives. However, paper primitives are thinner and softer than common basketry weaving materials such as bamboo strips or willow twigs, and the flat form factor also differentiates it from fiber wefts. Therefore, we conducted extensive weaving experiments initiating from paper weaving structures [57], to textile weaving structures [4, 13], and basketry weaving structures [3] to synthesize the extended woven design space for SkinPaper as shown in Figure 4.

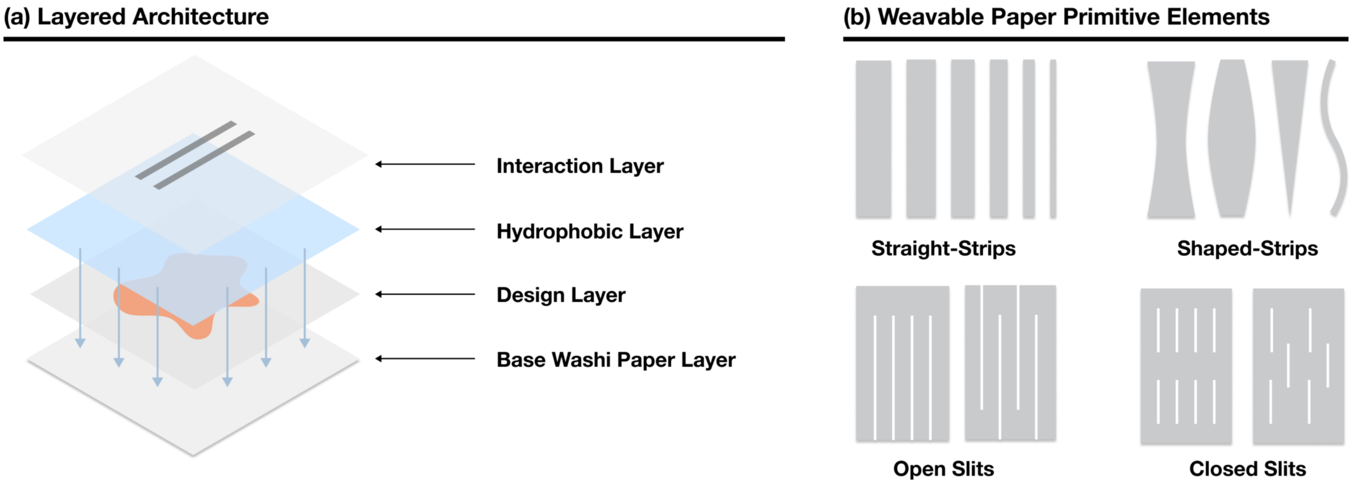

Figure 3: The paper primitive architecture is a multi-layer structure.

These woven structures can be further combined with paper folding techniques to create texture-rich on-skin interfaces. The presented structures have been prototyped with paper primitives and their corresponding weaving tools.

2D Pattern: The *single-layer* 2D patterns are beginner-friendly and easy to fabricate. They can be woven either freehand without tools needed or on a loom with fibers as warp. They provide a straightforward path for novices to weave on-skin interfaces quickly. It can also be used for rapid prototyping by more experienced makers to achieve a wide range of visual variances with limited materials. Even with the simplest 2D plain weave, one can create interactions, including a 2D capacitive touch sensing matrix or LED output matrix. The *double-layer* patterns allow inserting an additional layer of functional materials into woven structures, such as heating threads. These 2D patterns are suitable for cylindrical or planar body locations such as arm and back.

2.5D Texture: One unique property of paper is the folding and holding capability of the crease. This behavior is harder to achieve in soft materials such as fabrics or silicone. Through origami and kirigami techniques, folding creases on paper primitives with different patterns create unique textures for on-skin interfaces.

These textures are created during the weaving process, and no specialized tools are needed. With tweezers and scissors, we can easily use the same paper primitive material to fabricate textures, including foldable *fuzzy* and *square*, as well as protruded *dome* shown in the design space. These textures can be combined with different interactive layer designs for various input functions, such as pressure-sensing switches and output haptic actuation. These textures provide eyes-free interaction on easy-to-reach body locations, such as on the arm and behind the ear.

Unlike silicone-based on-skin interfaces where the material rigidity is set during the material mixing step, the SkinPaper textures can be created during the weaving process. This feature accommodates the intuitive and idiosyncratic processes and decisions when designing to allow for creative explorations for individual creators.

3D Structure: SkinPaper offers versatile three-dimensional woven structures to conform to specific body areas for various functionalities. The *cubic* structure interweaves three groups of paper primitives to form a three-dimensional cubic structure; the *concave* structure is woven through bundling two groups of orthogonal woven paper primitives; and by weaving two ends of strips separately, SkinPaper can form a *tubular* structure.

These structures can be directly woven on a mannequin or on the body to achieve the desired shape. These structures are suitable for difficult-to-conform-to body locations such as knees and shoulders that often pose a challenge for other on-skin substrate materials.

5 SKINPAPER FABRICATION PROCESS

5.1 Hydrophobic Washi Paper as Key Material

The key enabling material for SkinPaper is the hydrophobic washi paper primitive. Here, we present its four-step fabrication process.

Step 1: Customize Design Layer. Aesthetic customization of the paper primitive can be achieved with patterns, colors, or drawings. Compatible methods include using common water-based coloring tools such as inkjet printing, stenciling, or hand-applying watercolor paint. Materials such as thermochromic pigments can be added to water-based coloring in this layer.

Step 2: Render Paper Hydrophobic. Apply the off-the-shelf silicone-based spray (Kiwi Camp Dry) onto washi paper (Murakumo Kozo Select Natural) at a 12-inch distance and ensure the liquid fully saturates the paper (saturated paper should turn from opaque to semi-transparent). The coated paper should cure at room temperature for 24 hours. The application of silicone-based sprays does not alter the thickness of the washi paper and only requires a space with good ventilation (clean room facilities are not required).

Step 3: Apply Interaction Layer. We apply conductive materials or interactive elements onto paper. Compatible methods include applying metal leaves using stencils, printing with conductive ink, and adhering conductive fabric tapes.

Step 4: Process paper sheet into weavable paper primitives. To afford *weaving*, the resulting paper is cut into straight or shaped strips, or

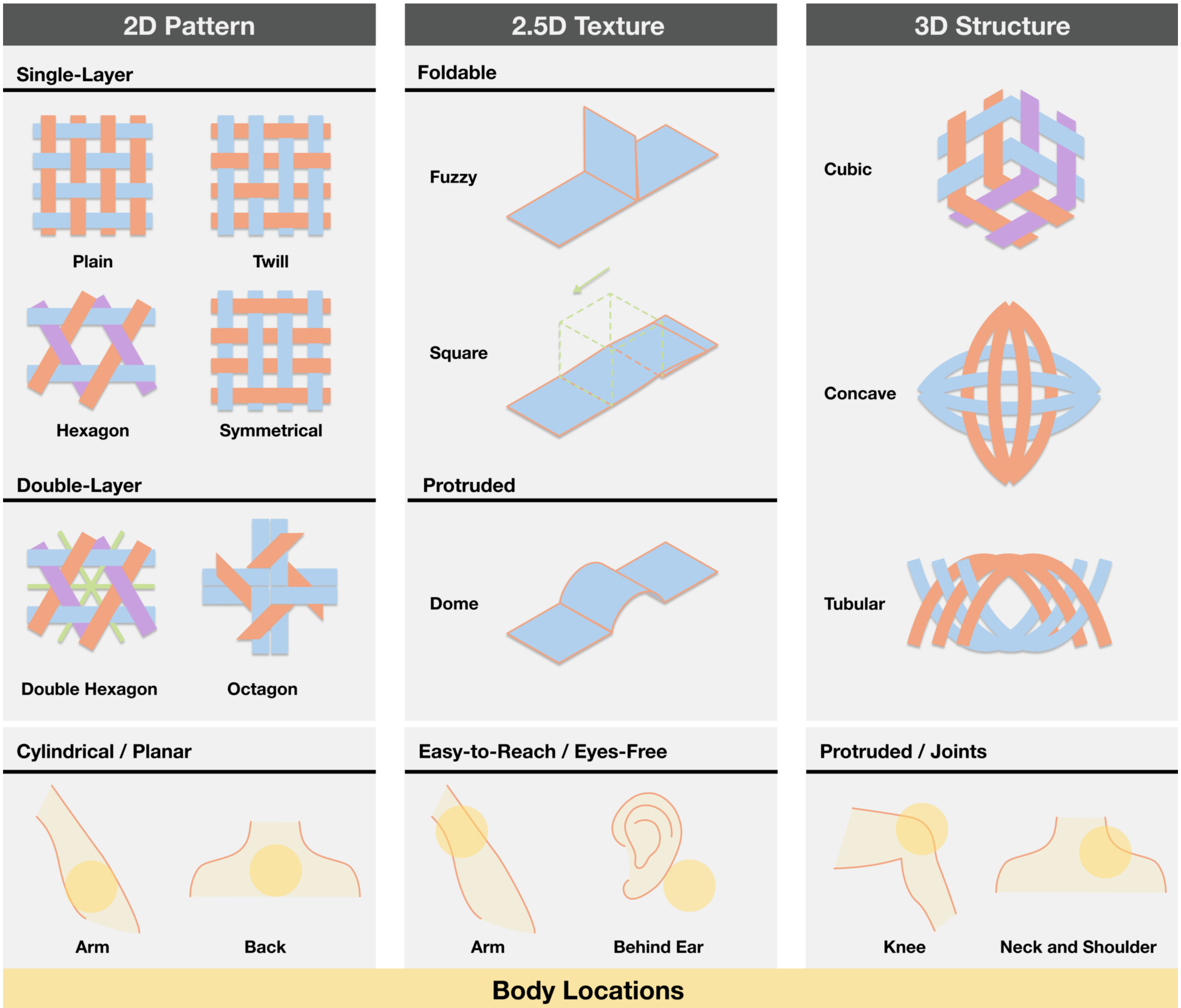

Figure 4: Woven Paper Structure Design Space

with slits for other materials to be woven *into*. This step can take place during the weaving process for impromptu adjustments.

5.2 Other Compatible Materials and Tools

As a fabrication technique, weaving supports the integration of a wide range of materials into the interface design. Below, we highlight other materials compatible with the paper primitives.

- *Functional Materials:* In addition to the interaction layer on the hydrophobic washi paper, weaving with conductive sheet-formed material can also integrate circuitry elements into woven interfaces. These conductive materials can function as conductors for circuit routing or electrodes for capacitive touch sensors and heating actuators. Weaving electronic components in wire-like forms such as shape-memory alloys (SMA) wires can expand functional capabilities. Other materials include conductive tapes, threads, and fabrics processed into strips.
- *Aesthetic Materials:* In addition to functional materials, SkinPaper supports the integration of various aesthetic materials with paper primitives, including pre-printed origami washi paper and washi tape, and fiber-based materials such as thin linen and silk yarn. For certain designs using fiber-based materials, a handloom or floor loom can be leveraged to attain a cloth-like structure.

5.3 SkinPaper: The 3-Steps Fabrication Process

The SkinPaper fabrication process is versatile, supporting customized design opportunities for both pre-planned and spontaneous

creation. It provides users with convenient tools for iterative prototyping and improvisation, crucial during early-stage prototyping.
Step 1: Preparation. To *weave* paper-based on-skin interfaces, the initial preparation step involves sketching and planning, hybridized from weaving [4], paper-crafting [57]and on-skin interface [20, 21] fabrication practices.

- *Drafting Paper Woven Interface.* We begin by determining the size of the device and its placement on the body. Then, based on the desired interactive function and the required circuit components, we choose the appropriate weave structure from 2D patterns, 2.5D textures, and 3D structures (Section 4.2). Next, we draft the length, width, shape, and strip width of the SkinPaper device.
- *Preparing Materials & Setting up Necessary Tools.* Based on the draft, we prepare corresponding paper primitive elements along with other tools and materials for weaving.

Step 2: Fabrication.

- *Weaving Paper Interface.* The choice of materials and tools implicates different weaving processes. The simplest pattern is a 2D plain weave that can be easily created by laying out warp paper strips onto a flat surface and inserting weft paper strips over and under each warp paper strip according to the pattern. To prevent shifting, the ends of the warps can be secured with tapes or pins. For 2D double-layer patterns, an additional layer of paper primitives is inserted after the first layer is woven. To weave 2.5D textures, hand tools such as tweezers are used to help with folding and creasing paper strips. To weave 3D structures, a basic 2D pattern is first woven on a flat surface and then transferred to a mannequin or human body to form the 3D shape. The fit is adjusted through on-body weaving. If fiber materials are used for a mixed material interface, the weaving process follows standard loom weaving techniques.
- *Circuit Integration.* After the woven structure is complete, surface-mount electronic components and circuit connectors can be attached to paper primitives through different assembly methods. For rapid prototyping purposes, conductive tape can be used for attaching wires to the paper primitives.
- *Components Sealing.* While the paper primitive is hydrophobic, assembled components and conductive traces on the interaction layer are not. After components are assembled, we seal the circuit with silicone-based conformal coating to protect components during wear. The circuit needs to be fully tested before sealing.

Step 3: Apply Skin Adhesive. We used skin-safe temporary tattoo adhesive (Silhouette Temporary Tattoo Paper) layered with polyvinyl alcohol (PVA) film (Sulky Solvy Water Soluble Stabilizer), a thin, biocompatible, and water-soluble sheet, as the adhesive to attach SkinPaper onto skin [60].

5.4 Putting It All Together: Design Affordances of SkinPaper: Supporting Low Floors, High Ceilings, and Wide Walls

Here, we discuss how SkinPaper can support a broad range of design goals and skill levels. The affordances of the SkinPaper design space allow for *"low-floors"* (easy entry) [54], *"high ceilings"* (enabling increasingly sophisticated projects), and *"wide walls"* (supporting a wide range of designs) [37, 59], as visualized in Figure 5. The

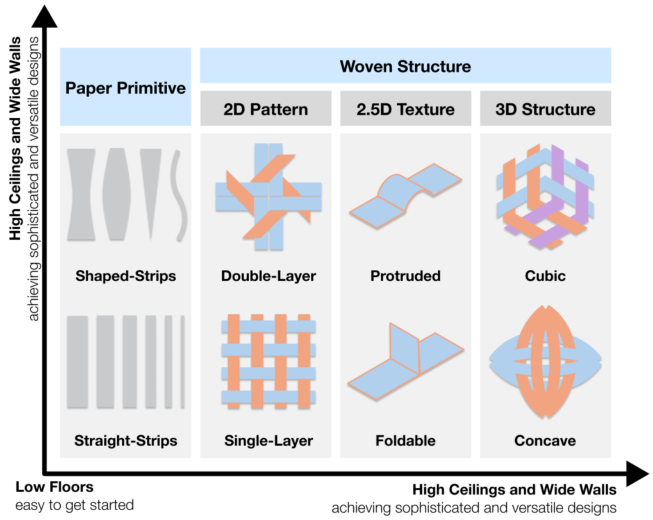

Figure 5: Design affordances of SkinPaper design space in terms of their ease to get started (low floors), and achieving sophisticated & versatile designs (high ceilings & wide walls)

choice of paper primitives and the woven structure defines the complexity of SkinPaper fabrication. SkinPaper designs can be as simple to make as children's paper-weaving crafts, and as complex as texture-rich swatches.
Low Floors: The familiarity of paper crafting allows SkinPaper to support a beginner-friendly fabrication process. With simple paper primitive configurations such as thick straight strips, users can easily fabricate interfaces with single-layer patterns. Beyond supporting ease of entry for beginners, this simplicity also offers rapid prototyping options for designers who need to quickly validate design ideas before fabricating high-fidelity prototypes.
High Ceilings: The tunable nature of SkinPaper primitives supports the transition from low- to high-fidelity prototypes. By altering paper primitive shapes, reducing paper primitive widths, or applying more complex weave structures, users can fabricate sophisticated and highly customized projects.
Wide Walls: SkinPaper's two-fold design space offers users a wide range of design possibilities. By combining different paper primitives with various patterns, textures, and structures offered in the SkinPaper design space, users can fabricate projects targeting a range of body locations, functionalities, and aesthetic styles. The mixed-material aspect of weaving also offers users room to combine SkinPaper with other weavable materials such as fiber, Washi tapes, and conductive fabrics.
An example design process: We illustrate how an end-user can take advantage of the various affordances of the SkinPaper approach in Figure 6. A designer has the idea of creating a touch-sensing input interface that is functional and decorative. They would start with a low-fidelity prototype using thicker (>6mm) SkinPaper primitives woven in a plain weave to test the design on different body locations. This iterative process helps them understand how curvature and movement influence the interaction on a mannequin or the body. The designer then chooses a specific design, such as

a shoulder sensing patch, then refines the prototype with thinner (3mm) SkinPaper primitives and complex 3D weaving structures. Finally, the designer could add texture to their design by weaving the paper primitives into 2.5D "fuzzy" textures. The final step is integrating circuitry to produce a high-fidelity prototype.

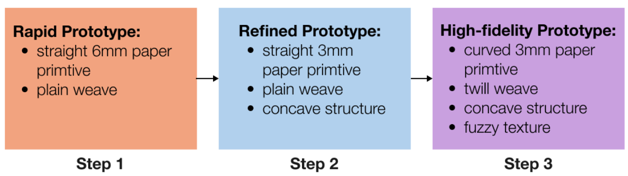

Figure 6: Example end-user SkinPaper prototyping workflow

6 UNDERSTANDING SKINPAPER

6.1 Characterization

To further understand SkinPaper, we characterized the material in terms of hydrophobicity, bendability, and tensile strength. This characterization guides users to choose the optimum paper primitive design and woven structure to address the design and functional requirements of the desired on-skin interface.

Hydrophobicity: Hydrophobicity, or water repellence, is critical for on-body wear. We assessed SkinPaper's hydrophobicity by measuring the static contact angle to the paper surface [40]. This was obtained by dispensing a 10 μL droplet of water onto the paper surface and capturing a photo of the droplet in profile using a digital microscope. If the static contact angle exceeds 90 degrees, the surface is hydrophobic. We ranked the efficacy of different treatment methods by calculating the average contact angle for each. The result is plotted and compared in Figure 7(a). Silicone-based spray conferred a higher contact angle than silanization with a 6.3 v/v % solution of trichlorododecylsilane [55, 56], an advanced treatment method pioneered in the material sciences. Silicone-based spray products such as Kiwi Camp Dry are better suited to fabricating SkinPaper primitives as they can be purchased off-the-shelf, do not require clean room facilities or a fume hood, and yield better results for hydrophobicity and durability.

Strip Width and Bending Rigidity: The rigidity of on-skin woven paper structures can be modulated by cutting paper strips to variable widths before weaving. To characterize the relationship between bending rigidity and the width of woven strips, we wove a series of 50 mm x 150 mm swatches at strip widths ranging from 2mm to 8mm using the plain weave technique. The warp and weft were of uniform length for each swatch. All swatches were woven using the same type of washi paper (Murakumo Kozo Select Natural) treated with Kiwi Camp Dry Heavy Duty Water Repellent spray. We used the FAST Bending Meter to measure the free bending length of the different swatches to calculate the bending rigidity of each swatch μN·m. Bending rigidity is extrapolated from bending length B by the equation $B = W \times c^3 \times 9.81 \times 10^{-6}$, where c is equal to the bending length (mm) given by the FAST meter and W is the mass per unit area (g/m^2). Figure 7(b) demonstrates a general trend of bending rigidity increasing in tandem with strip width. We use

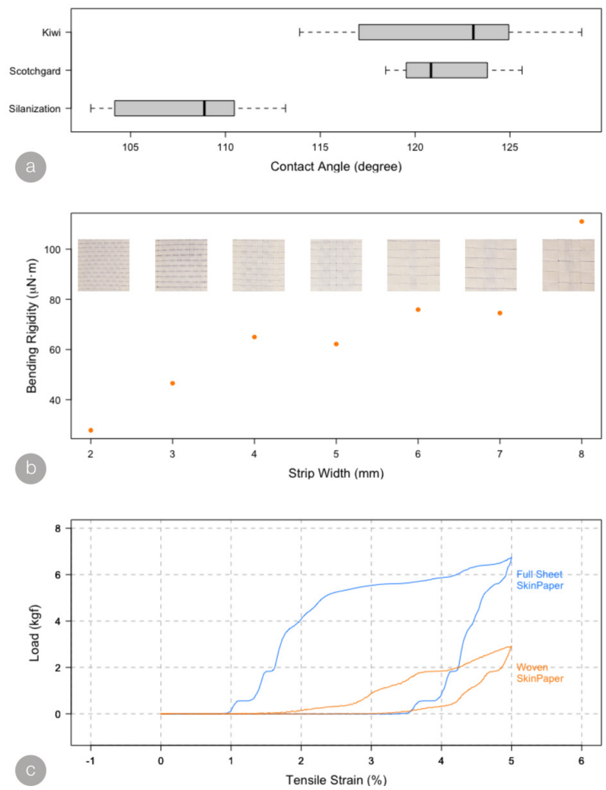

Figure 7: (a) Contact angle measurements of washi paper with three treatments: Silanization with trichlorododecylsilane, the Scotchgard Sun and Water Shield, and the Kiwi Camp Dry spray. (b) Bending rigidity characterization of swatches woven with washi paper at different strip widths. (c) Tensile strength comparison between full sheets and woven hydrophobic washi paper

the bending rigidity comparison as general guidance for choosing strip width for different on-skin applications.

Tensile Strength: On-skin substrates should remain intact under reasonable tensile strain. We characterized the tensile strength of woven SkinPaper using the Instron Universal Testing System (Instron 5566). We prepared test materials in sizes of 100mm by 150mm and tested them by applying a maximum of 5% pulling length on the long side. Figure 7(c) compares the tensile strength of a full sheet of SkinPaper and a SkinPaper swatch woven from 2mm-wide strips. The graph demonstrates that woven SkinPaper takes less load force to achieve the same tensile strain as unwoven SkinPaper, indicating that it is significantly easier to stretch.

6.2 Wearability Study: Durability of Worn SkinPaper Devices

We aim to understand the *wearability* [29] of the system, which includes mechanical durability, water resistance, ability to maintain electrical functionality, and comfort when worn on the skin. Our methodology of evaluating wearability when worn directly on the skin (instead of via bench tests or placement on mock silicone skins) builds on research guidelines for increasing the ecological validity in evaluating on-skin interfaces [20, 29, 60]. Importantly, we focus on evaluating the wearability of the SkinPaper material, not including rigid microcontroller units, which are a limitation of all current on-skin interfaces.

Apparatus: We fabricated 5mm width paper primitives with a color-printed design layer and applied 2mm-wide traces of gold leaf. We wove the paper primitives in a 2D plain weave pattern and trimmed them into 1.5×1.75 inch patches (Figure 8). Each sample contains four conductive paper primitives: two woven in the warp and two in the weft. These sample patches serve as simplified yet representative SkinPaper devices; their interaction layer is an example of the SkinPaper design space.

Procedure: We recruited 10 participants (6 female), aged between 24-33 years ($M = 26.5 \pm 3.26$). At the start of their workday, we met participants to apply SkinPaper patches on their inner non-dominant forearms. Participants wore the devices for 8 hours and engaged in daily activities. Each hour, participants measured the conductive traces with a multi-meter and visually inspected the patch, logging the mechanical and electrical condition of the patches in a provided form. After 8 hours, participants removed their patches by themselves. The process is followed by a post-study survey and semi-structured interview.

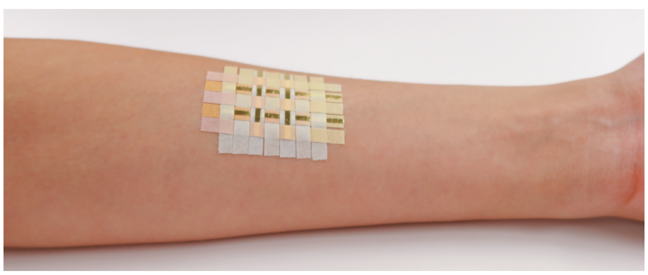

Figure 8: Wearability study patch: on skin testing of durability, comfort, and functionality of SkinPaper patch.

Results:

Mechanical Durability: 9 of 10 devices remained attached to participants' bodies for 8 hours. The remaining device adhered for 7 hours. Five devices peeled off slightly at the edges. Participants agreed that the devices remained well-attached to the body throughout the day, with a median of 6.5 on the Likert scale (1 = strongly disagree; 7 = strongly agree). According to participants, activities that caused the device to peel off included putting on and removing clothing, picking up a backpack, and typing on laptops.

Electrical Functionality: All the devices' conductive traces maintained electrical connection throughout the 8 hours.

Comfort: Participants' perceptions of wearing the device included "not noticeable" and "like a bandage on the skin," and rated being accustomed to the device with a median score of 6 (1 = strongly disagree, 7 = strongly agree). No participants reported concern regarding the safety of wearing the device.

7 EVALUATING SKINPAPER DESIGN PROCESS

7.1 Case Studies

We present a total of 8 case studies generated through our research through design [14, 73] methodology to explore design opportunities for paper-based on-skin interfaces. These explorations offer insights into the creative capabilities of the SkinPaper design space, providing generalizable design solutions for future SkinPaper applications. We present case studies of each paper weaving structural dimension: first examining three case studies of 2D patterns, three case studies of 2.5D textures, and two studies of 3D structures that can directly envelop body locations.

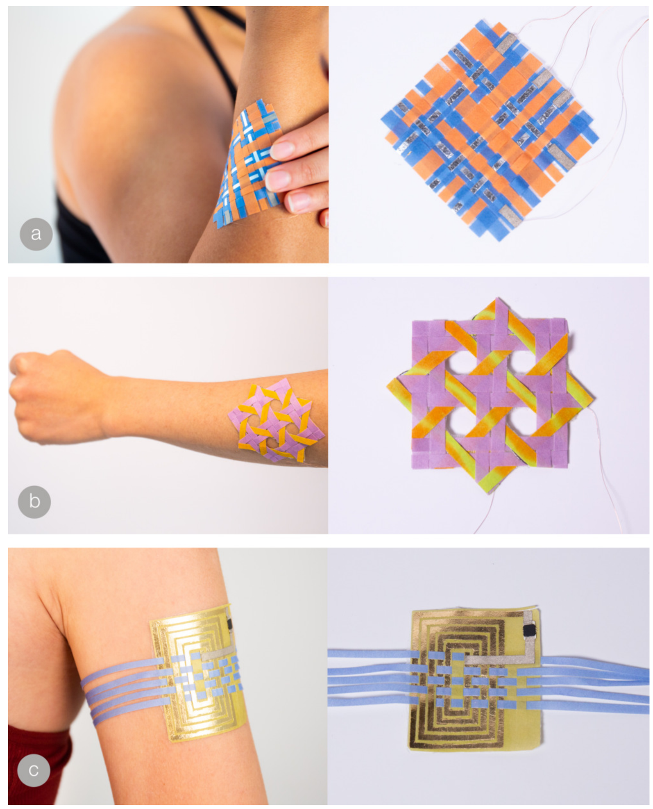

Figure 9: 2D Patterns: (a) Plain Weave Touch Sensing Matrix. (b) Double Weave Thermochromic Patch. (c) Twill Weave into NFC Tag with Cut Slits.

7.1.1 2D Pattern. **Plain Weave Touch Sensing Matrix:** In the SkinPaper design space, the geometric shape of SkinPaper primitives can come in a wide range of sizes and shapes with a simple plain weave pattern. Our sample shows a touch-sensing matrix using a 2D plain weave pattern to weave the SkinPaper primitives in mixed strip width (Figure 9(a)). This sample is also created in an improvised fashion: we fabricated a bundle of conductive and non-conductive paper primitives and chose from the supplies as needed during the weaving process.

Double Weave Thermochromic Patch: The SkinPaper design space offers a wide range of double-weave patterns. This thermochromic patch uses a 2D octagon basketry weave pattern to incorporate thermochromic painted paper primitives into a double weave structure (Figure 9(b)). Non-thermochromic SkinPaper primitives function as an underlying insulation layer while conductive thread woven in-between layers function as the resistive heating traces for thermochromic activation.

Twill Weave into NFC Tag with Cut Slits: In this sample, we fabricated the SkinPaper primitive with an NFC coil as the interaction layer (Figure 9(c)). We chose $7 \times 9cm^2$ as the coil dimension and gold leaf as the conductive material and used conductive fabric tape to attach the NFC chip (NXP MF1S5030XDA4) [21]. We used a closed-slits cutting pattern in the SkinPaper design space to cut slits for interweaving paper primitives. We used a 2D 2x1 twill pattern in this sample to weave long SkinPaper strips into the NFC coil pattern to form an armband.

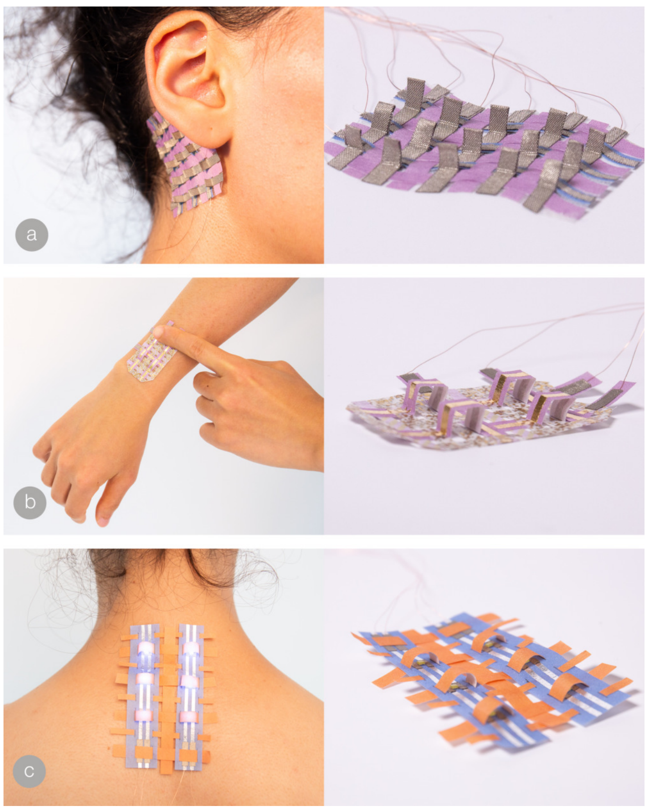

Figure 10: 2.5D Patterns: (a) Behind Ear Fuzzy Weave Touch Input. (b) Collapsible Textures as Pressure Input. (c) Protruded Dome Texture for LED Diffusion.

7.1.2 2.5D Texture. **Behind-Ear Fuzzy Weave Touch Input:** The SkinPaper design space affords foldable 2.5D textures. These textures can be employed in interfaces where users cannot see, such as behind the ears. In this way, users can be guided by the haptic sensations of the textures. This sample combines serpentine-shaped paper primitives with a 2.5D fuzzy weave texture to create a behind-ear input device (Figure 10(a)). For serpentine paper primitives, we used conductive fabric tape as the interaction layer material and woven and folded conductive fabric tapes in plain weave patterns. This patch functions as an input switch matrix of 3 columns and 5 rows of switches and can detect various touch gestures.

Collapsible Textures as Pressure Input: Washi Tapes are decorative tapes with pre-printed decorative graphical patterns. This sample explores how washi tape can be combined with the SkinPaper paper primitives to weave foldable 2.5D textures (Figure 10(b)). We wove gold leaf trace applied SkinPaper primitives with a golden-colored washi tape in the plain weave pattern, with folded rectangular textures. Aesthetically, the washi tape provides easy yet unique decoration to the sample. Functionally, the washi tape's adhesive backing maintains the weaving pattern during the weaving process so that no clips or tools are needed.

Protruded Dome Texture for LED Diffusion: Inspired by washi paper used as a light diffuser for light fixtures, the SkinPaper primitive is translucent and can be used to create various on-body light diffusing effects. In this sample, we used protruded 2.5D dome-shaped weaving texture to create a diffuser for two rows of surface-mounted LED (Figure 10(c)). The base paper primitive is cut with closed slits, and strip-shaped paper primitives are woven into the slits to create textures. Silver leaf is used as the interaction layer trace material, and conductive fabric tape is used to attach the 1206 packaged surface-mounted LEDs. This sample creates an expressive on-body flashlight for activities such as biking in the dark.

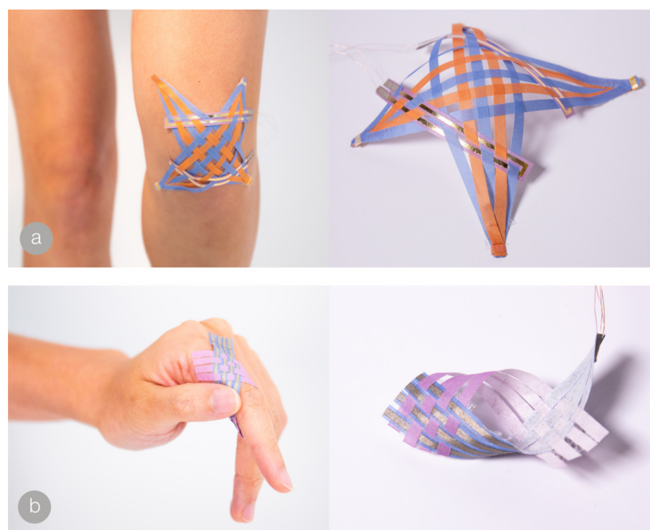

Figure 11: 3D Patterns: (a) Knee Heating Patch in Concave Structure. (b) Tubular Finger Touch Sensing Slider.

7.1.3 3D Structure. **3D Heating Patch for Knees:** The SkinPaper design space offers 3D structure weaving techniques to conform to body locations such as body joints. In this sample, a heating patch for the knees is made with the bundle and boxed 3D structure (Figure 11(a)). The heating material has open slits pattern and was interwoven into two different groups of orthogonal woven strips, with the ends of each group of strips bundled to the conform knee area. The sample demonstrates an easy on-mannequin weaving process starting with a basic plain weave on a table and then shaped into a concave structure on the mannequin.

Tubular Finger Touch Sensing Slider: This sample explores how paper primitives of narrow width can be used to weave 3D structures for refined body locations such as fingers (Figure 11(b)). We used 3D tubular structure to weave 2mm width paper primitives to create a 4-segmented touch-sensing slider. This sample examines the on-body weaving process: we placed the tubular-shaped woven base onto our fingers to adjust the size and shape of the structure.

7.2 Workshop Study

We conducted a design workshop study with four participants to understand end-users' iterative design process from low- to high-fidelity prototyping. We aim to observe the feasibility of rapidly creating a low-fidelity prototype using SkinPaper, to the "high ceiling" and "wide walls" potential of SkinPaper's design affordance. We also aim to discover how individuals with diverse weaving experiences adapt this new fabrication approach to their practices. Hence, we recruited participants with weaving experience ranging from 1 year to 40 years.

Participants: We invited participants with varying levels of experience in basketry weaving, fiber arts, and paper crafting with the following criteria: (1) Artists are familiar with basic weaving and have worked with paper as crafting materials; (2) Prior experience with computational technology and circuitry is not required. We conducted the study with four artists (all female) with ages ranging from 20 to 70. The participants (anonymized by pseudonyms) are Luna, a textile artist and engineer with nine years of experience in textile weaving; Ruth, an artist with over 40 years of textile and basketry weaving experience who runs her workshop; Iris, a textile designer with two years experience in textile weaving and one year in bamboo basket weaving; Scarlet, an undergraduate in fashion design, with one year of experience in textile weaving and makeup art. We provided a $40USD gift card as gratuity.

Workshop Procedure:

(1) Session 1: Briefing and brainstorming session (1 hour). We introduced the fabrication process, demonstrated sample swatches, materials, and weaving techniques, and discussed design directions with participants via a Zoom session. Participants were given one day to individually plan their project, where they could ask researchers questions regarding materials and functional components. Because participants had no prior knowledge of prototyping electronics, sample circuits were provided to demonstrate the capabilities of SkinPaper.
(2) Session 2: Crafting session (2.5 hours). Artists came to the lab to fabricate their projects. Researchers assisted artists with circuitry integration toward the end of the crafting session.
(3) Session 3: Post-study semi-structured interview (30 min). We conducted a post-study semi-structured interview. The interview was audio recorded and later transcribed for analysis using grounded theory approach [6].

Luna' Project: 3D Shoulder Warmer. As a textile artist, Luna's weaving integrates geometric shapes into textiles. With SkinPaper, she created a shoulder piece that eases pain with controlled heating. Luna wove with silk as warp on a floor loom (Figure 12), and triangular paper primitives embedded in the weft. In weaving, she iterated on different weave patterns by removing and inserting the triangular-shaped paper primitives. She was impressed with the speed of weaving with shaped paper strips compared to other tapestry weaving techniques. The woven piece was taken off the loom and shaped into a 3D arch by pulling the warp yarns on a mannequin. The 3D structure beautifully flowed over the shoulders and around the collarbone thanks to the paper primitives' materiality.

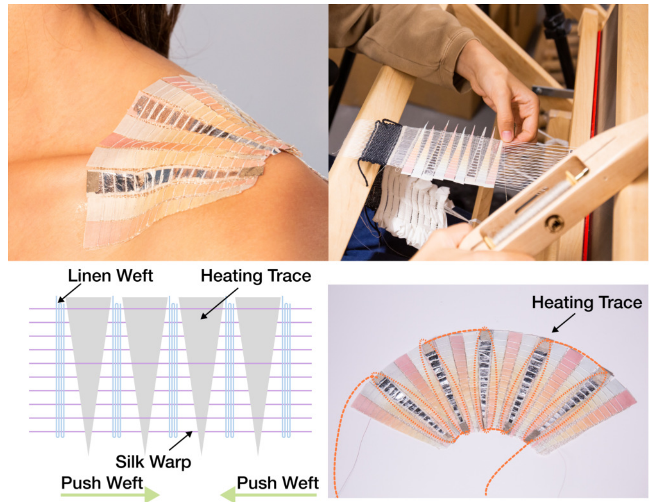

Figure 12: Luna' Project: A 3D shoulder warmer for easing shoulder pain woven on a floor loom.

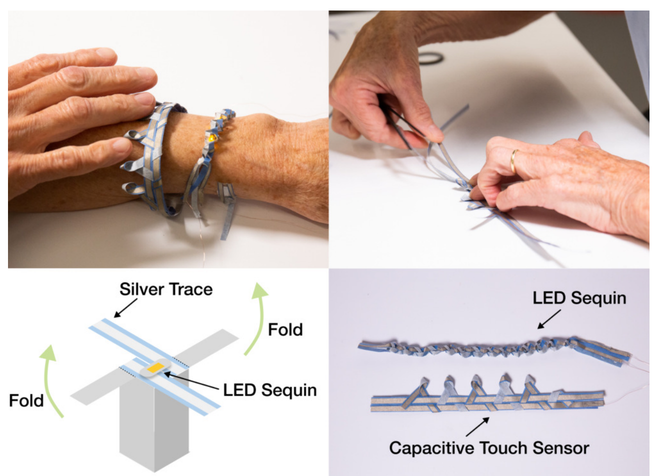

Figure 13: Ruth's Project: A 2.5D touch-triggered bracelet.

Ruth's Project: 2.5D Light up Bracelet. Ruth, a weaver and sculptor with 40 years of weaving experience, created a light-up bracelet pair using two unique weaving techniques with conductive tape as the conductive material(Figure 13). She first prototyped with thick strips (6mm) to familiarize herself with the material and circuit, then refined the prototype with thinner strips. The touch-sensing bracelet features a cone-shaped texture as a touch sensor and is woven with a binding technique with the looped weft tucked under the warp, without the need for adhesive. The light-up bracelet utilized paper's translucency to diffuse light and created a stretchable structure through a loose boondoggle weaving technique. Both bracelets' circuitry was connected, and the lighting bracelet lit up when she touched the sensing bracelet. Ruth found thicker primitives easier to handle, but precision weaving with thinner strips required more practice.

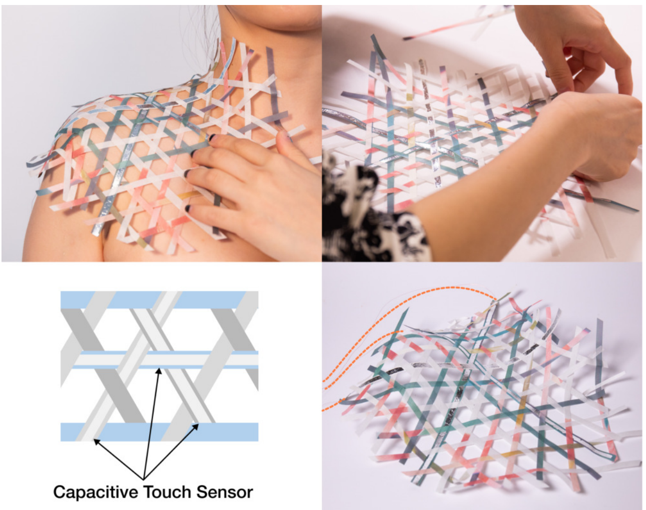

Figure 14: Iris's Project: A 3D hexagon weave touch sensing harness triggers different tones.

Iris's Project: 3D Hexagon Weave Touch Sensing Harness. Iris's basketry weaving practice uses bamboo strips to weave 3D sculptures. Her project is a neck and shoulder harness that senses touch on the neck to trigger different tones played from a computer (Figure 14). She viewed the harness as a connection between the body and nature and was interested in using touch to interact with the sound in her surroundings. She chose plant and flower prints to connect her aesthetic expression with her design concept. She applied a bamboo weaving technique: a hexagonal weaving pattern, to this design. She wove this piece on a flat surface before applying it to a mannequin. Although the material was much softer and thinner than bamboo, she was surprised to see that it still held the structure due to its interlocked feature.

Scarlet's Project: 3D Movement Sensing Headpiece. Scarlet has one year's experience weaving tapestries with thick yarns. In her makeup art practice, the eye is often the focal point. With this project, she designed a one-sided headpiece that embellishes the face and senses head movement (Figure 15). She explored weaving with serpentine-shaped strips at an angle and employed paper fringes with conductive yarn as a textured touch sensor on the face. Using washi tapes, she wove the paper primitives onto a mannequin face and was impressed by how paper can be customized for weaving, unlike yarns' fixed thickness. She noted that the paper primitives are thinner and require more careful handling than yarn.

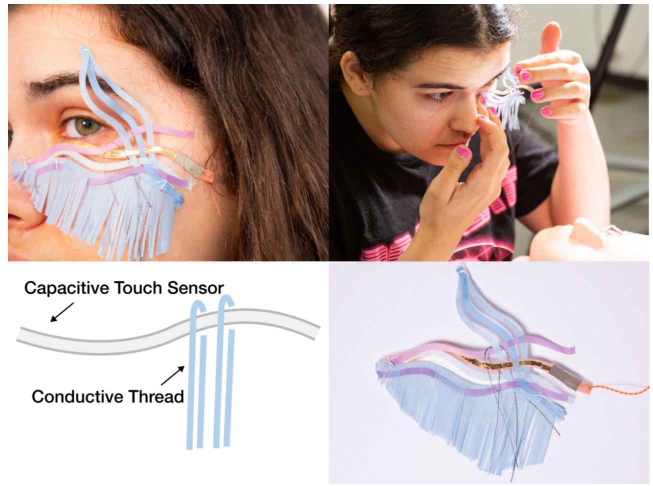

Figure 15: Scarlet's Project: A 3D headpiece employed paper fringes as an on-face textured touch sensor.

Observations. We summarized our observations from the crafting session and post-study interview into four themes.

- *Paper as a Easy-to-use and Familiar Material.* All participants prototyped a woven structure with the prepared paper primitives within a fixed time frame. Even though treated washi paper is a new material for some participants, the familiarity with paper provided a handle for them to get started, emulating our expectation for the accessible fabrication approach. All participants completed multiple iterations during the workshop study. Ruth expressed how frequently she wove paper objects with her grandchildren as a simple craft but never completed a paper art project. Scarlet noted that: *"paper is pretty accessible to manipulate to just the average person"*. In Luna's design, she contrasted the rapid process of printing a gradient design on SkinPaper and trimming into geometric shapes versus the time-consuming process of weaving a gradient color block with yarn.
- *Versatile Paper Weaving Design Opportunities.* We observed that the ability to adjust the properties of paper during fabrication highlights the versatility of paper as a material for expressive interfaces. Luna explains *"It's like there's a set of parameters and you can do all these crazy things in this set."* Luna and Iris examined the design process of weaving in 2D and shaping the structure into 3D after weaving. Luna incorporated weft shaping techniques, while Ruth incorporated basketry weaving techniques of interlocked structures, demonstrating the notion of "wide walls" discussed in Section 5.4. Further, we observed that although all designs were pre-planned, they all went through multiple iterations. Iris and Scarlet explored on-body weaving as an iterative design process, allowing them to adjust the design while weaving.
- *Bringing structure to on-body interactions.* All participants explored 2.5D textures or 3D structures, pushing the expectations of conventional weaving standards under consistent time constraints. Luna commented that the property of the SkinPaper material combined with the 3D weaving structure resulted in an accessory that draped around her collarbone, unique from her

other woven work, which is taken flat off the loom. Iris compared this practice to bamboo weaving, which requires extensive pre-process preparation. Additionally, the paper's malleability allows her to reshape and manipulate the entire woven structure as opposed to Bamboo weaving. The same woven piece can be applied to different body locations or worn by different wearers and still conform to their shape. This material property makes it suitable for on-body interactions and fits every individual. Furthermore, the layered structure also serves as an instinctive representation of circuitry connectivity, simplifying the comprehension of the design for individuals lacking circuitry experience.
- *Hybrid On-Body Form Factor.* Luna compared this project with her previous textile work and noted the unique on-body interactions created by combining paper weaving and circuitry straddled garments, tattoos, and jewelry. She described the silver leaf traces as resembling silver jewelry while the lightweight aspect of the paper *"combined with the skin directly like a tattoo"*. Similarly, Ruth, who does not typically wear jewelry, found this paper-based interface more comfortable and lighter than other wearables. Participants saw SkinPaper devices as a hybrid form factor, with the potential for generating new hybrid aesthetics [63].

8 DISCUSSIONS, REFLECTIONS, AND FUTURE WORK

New Design Strategy for Crafting On-skin Interfaces via Paper. As the outcome of the research-through-design process, SkinPaper affords a new user-friendly design strategy for making on-skin interfaces through the twofold design space for paper weaving. Below, we reflect on the unique properties of the SkinPaper approach through a qualitative examination of its unique design affordances in comparison to other on-skin interface materials and their fabrication processes.

- *Versatile Materiality.* SkinPaper leverages the versatile materiality of paper to lower the barrier for rapidly prototyping on-skin interfaces. By tuning the size and shape of paper primitives, the material characteristic would be flexibly tuned during the crafting process. Unlike silicone- and hydrogel-based on-skin interfaces [19] where the material rigidity is set during the material mixing step, the SkinPaper textures and structures can be created across different stages of the prototyping process. This property affords expressive creations during the crafting process.
- *On-the-Fly Adjustments and On-Body Fabrication.* Creators easily modify the design during the creation process by swapping paper primitives or reconfiguring woven structures to conform to body locations on the spot. This feature accommodates the intuitive and idiosyncratic processes allowing for creative explorations. On-body weaving process offers an intuitive way to rapidly prototype on-skin interfaces at low cost and directly on the body surface, similar to the draping process in fashion design where sketches are three-dimensionally prototyped on a mannequin. This improvisational design approach supports creation and exploration, which is critical, especially for on-body design [46], yet unrealized by current fabrication approaches.
- *Reusability Towards Sustainable On-Skin Interfaces.* The SkinPaper workshop study showed that the samples created were reusable: after being peeled off from the user's skin, the woven piece can be reused by re-applying a layer of PVA skin adhesive. This property can be hard to achieve through other tattoo-decal-paper-based on-skin interfaces [21, 67]. Moreover, each individual paper primitive can be reused in different weaving pattern designs, while PDMS- and hydrogel-based on-skin interfaces [19, 66] have fixed forms once molded. In the future, it could be fruitful to investigate strategies for reusable paper-based on-skin interfaces.

Opportunities for Extended Weaving Investigations in HCI Research. Although the HCI community has extensively researched textile woven interfaces [11, 17, 48], paper and basketry weaving have not been met with the same level of exploration. As a regional and cross-cultural-specific craft, the materials of basketry weaving are not universally standard: for example, bamboo strips are commonly used in East Asia, and willow bark is commonly adopted in North America. This results in diverse weaving patterns and locally distributed documentation. Furthermore, paper weaving is often seen as a children's craft and is less examined in the arts. Compared to textile weaving, the other two weaving types have less documentation and unified terminologies yet offer unique design opportunities. We see an opportunity to expand the weaving circuitry spectrum in HCI research to incorporate more multi-material weaving practices into the e-textile and wearable realms.
Towards Fully Integrated Paper-Based On-Skin Interfaces. SkinPaper design explores circuit functionalities, but to realize a fully integrated woven paper circuitry, further hardware integration is required. In the future, we can utilize flexible PCB that can be customized into 2D shapes that align with the design of SkinPaper primitives to create robust yet seamless circuit integration.

9 CONCLUSION

We present SkinPaper, a fabrication approach using silicone-treated washi paper to weave lightweight and easy-to-fabricate on-skin interactions. We defined a twofold design space that enables users to fabricate a wide range of on-skin interactions in rich 2D patterns, 2.5D textures, and 3D structures. We identified hydrophobic washi paper as the key material. Our user-friendly fabrication approach enables creators to use off-the-shelf materials to fabricate SkinPaper with customized design opportunities. We characterized the SkinPaper material in terms of its hydrophobicity, bending rigidity, and tensile strength. In the wearability study, we examined the durability and comfort of paper-woven on-skin interfaces.

We present eight case studies to examine the functional and aesthetic affordances of SkinPaper. In the workshop study, participants combined the fabrication approach with their art practice and created on-skin interactions across various wearable scales and functions. The study revealed the benefits of weaving with paper, a familiar and versatile material. Our study observations highlighted the opportunities of introducing structure to on-body interactions and the extensiveness of the hybrid on-body form factor.

Through our extensive Research through Design [14, 73] investigations, we reflect on how paper affords a new design strategy for on-skin interface fabrication, especially in its capability for on-the-fly adjustments, on-body fabrication, as well as its versatile, tunable materiality. The global familiarity of paper, paired with our identified design space encompassing rich woven structural capabilities, also brings forth the creative potential of SkinPaper in supporting a broad range of design goals: from easily getting started, to creating increasingly sophisticated and diverse designs.

Through SkinPaper, we envision expanding on-skin interface fabrication to broader audiences, empowering diverse populations to make, design, and co-define this emerging, next-generation form of wearable computing.

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